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The Differences in Shape Stability for Hornbeam (*Carpinus betulus* L.) Lumber with and without Spiral Grain

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Abstract: Spiral grains are one of the most important tree growth defects that can remarkably affect the shape stability of lumber. This growth defect is observed by an oblique arrangement of axially oriented cell elements in the wood. This research focused on identifying and measuring selected shape changes caused by the spiral grains in the log. Hornbeam logs with spiral grain and with no spiral grain aged 60 and 52 years were selected to detect shape changes. Following the research and the norms of STN EN 1309-3 (49 1013), DIN (4074-5), and ASTM D245, it can be stated that spiral grain is an essential factor affecting the shape stability of hornbeam lumber. In the case of lumber with spiral grain, the spiral grain increased by up to 8° within three months. The warp of both types (bow, crook) increased exponentially throughout the study, peaking between the third and fourth week with an increase in warp bow of 26 mm and 17 mm in warp crook.

Keywords: hornbeam; spiral grain; shape changes; lumber; bow; crook

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1. Introduction

The accuracy of the log dimensions, the material dimensional stability, stiffness, strength, resistance to rot, density, or even the appearance of the material are some of the requirements that the customer may place on timber. One of the most common reasons customers avoid using wood, e.g., in timber structures, is lower dimensional stability. Visible changes in shape, leading to unacceptable difficulties in wood processing, are the most significant adverse effects of timber construction. Since spiral grain in wood causes issues in timber structures, there are reasons why wood is often not preferred for use in structures and is replaced by other materials, such as concrete with steel. Moreover, the negative impact of the spiral grain on the quality of timber and its products can be observed, as the fibers copy the curvature but not the saw cut. Such a log has lower strength properties than a log with no spiral grain. When processing logs, the size of the spiral grain must be considered. This fact is essential in the case of a warp twist because it negatively affects the tensile properties of wood. Logs with extreme spiral grain are unacceptable as the material is further processed. Depending on the purpose of use, the spiral grain plays an essential role in wood utilization; therefore, it was also included in the classification criteria [1]. The changes in the mechanical properties (Hickory, Ash, Elm, Beech, Maple) due to the spiral grain were also investigated in [2]; it was found that the grain deviation angle (from 0° to 15°) from the rectilinear pattern has a significant impact on the values of mechanical properties. For all species (Hickory, Ash, Elm, Beech, Maple), they investigated an absolute decrease in value exceeding 50% of the initial value; this decrease was even over 60% for the two examined wood species. These findings have direct implications for the construction industry, highlighting the need for careful consideration of spiral grain in timber selection and utilization. Similar results were discovered in [3]. The authors investigated the effect of the global slope of grain on the bending strength of scaffold boards. Results showed that the magnitude of the slope of grain has a very marked effect on its bending strength

(boards were 24% weaker in comparison with boards made of equivalent timber quality). The impact of spiral grain formation on timber quality is not just a theoretical concept. It is a practical concern that is reflected in the standards, which clearly state the permissible curvature values when sorting timber [4]. For instance, according to the American ASTM standards, left-handed logs and subsequent products may not be suitable for certain applications, such as ceiling beams, rafters, purlins, etc. However, material with left-handed fibers can still be used in timber structures for load-bearing walls, highlighting the nuanced understanding and application of this knowledge in the industry.

The formation of spiral grains is controlled genetically. However, environmental factors also have a noticeable influence on spiral grain—genetic predisposition, older age, position, type of cell formation, rotation of the earth, or the gravitational effects of the moon [5–8]. Most of the data from previous studies indicate that tortuosity formation originates in the cambium and may be associated with cell division in this region. This process can be regulated according to studies of the plant hormones [9]. Three methods of cell division are thought to cause spiral grain. The angle of rotation of the spiral grain depends on the transverse divisions of the vertically oriented cambial cells. The cumulative effect of transverse divisions accompanied by poor growth has received much attention for over a century [10]. Poor growth alone with no transverse division, an essential factor in spiral grain, means that the fibers in the cambial layer slide past each other, changing their relative orientation, i.e., the two ends of the cells move in opposite directions, resulting in a slight rotation of the cells. Therefore, the angle between the cell and the pith changes. The third process, which is determined to have a significant effect on the formation of spiral grain, is the imperfect division and differentiation of cells that accompany such divisions, i.e., the division is considered incomplete if the partially newly formed cell wall does not extend from one end of the cell to the other. However, there is still no evidence that these theories are more likely or, conversely, less likely to be correct than others [11].

In several articles, the authors confirm that standing on rocky and one-sided terrain produced significantly more trees with spiral grain than those on open stands with irregular spacing between trees. Border trees in stands are often dominant and have wider annual rings and relatively large living crowns compared to average trees in the same stand. According to several studies, the trees at the border of the forest have more pronounced spiral grains than trees inside the forest [12].

The shape instability of the hornbeam tree (*Carpinus betulus* L.) could be better for woodworking. Its sensitivity to moisture and low durability prevent its use outdoors [13]. This is one of the reasons why it is mainly used as firewood. Shape stability is an important property that significantly affects the final product based on changes in its mechanical properties. In the Slovak Republic, timber structures can only be built from Spruce wood (*Picea abies* (L.) H. Karst.) or certified timber, but why not use hornbeam timber? There is a significant amount of hornbeam, and in the future a combination with Beech (*Fagus sylvatica* L.) could be used, as these two trees occur in the same forest stands, which could save funds for mining and construction material for construction, e.g., in timber construction, where an upward construction trend is still expected.

Shape changes caused by changes in humidity during drying or operation are the main problem of wood materials intended for timber structures. Changes in moisture content are accompanied by significant shrinkage or swelling of the material. The stability of timber is often connected with the cylindrical geometry caused by the growth rings, the wood material's orthotropic nature, and the wood fiber's tendency to grow spirally around the trunk; this is often considered the most damaging deformation of timber [14]. Forsberg and Warenjö [15] found that the angle of the spiral grain on the surface of the trunk and the slope of the angle of the fibers of the curve are strongly correlated with the rotation angle. Ekevad [16] described the basic mechanical understanding of the causes of shape changes associated with the tortuosity of fibers. Ormarsson [17] states that the spiral grain angle is the angle between the pith and the spiral grain direction. This angle often shows a radial deviation in round wood. Therefore, the spiral grain angle is one of the most critical

parameters in shape changes linked to warps. It also affects warp bow but almost does not affect transverse curvatures [18]. Shape changes in dried lumber can depend on several factors. One is the original position of the lumber before the log's breakdown: several authors [18–21] addressed this issue by focusing on the original position of the log by subsequent comparison of shape stability between produced radial and tangential lumber. This study showed a significant redistribution of stress when the logs were cut, resulting in a distinctly visible warp bow, especially on the side lumber. The warps created during the processing of the logs and the remaining growth stresses affect the shape changes after drying [20].

The main goal of the presented research was to analyze and compare the shape stability of the lumber that contained or did not contain spiral grain during natural drying of the wood hornbeam (*Carpinus betulus* L.).

2. Materials and Methods

The logs of Hornbeam (*Carpinus betulus* L.) were selected in the district of Ziar nad Hronom (Slovakia), in the cadastral territory of the municipality of Hronska Dubrava, with an average altitude of 457 m above sea level (ASL). The logs were yielded by the University Forest Enterprise in Zvolen. The geological substratum in this location consists mainly of andesites and pyroclastics. The exact sample location is shown in the map marked in green (Figure 1). The forests in this area are dominated by deciduous trees, mainly Beech (*Fagus sylvatica* L.) and Hornbeam (*Carpinus betulus* L.).



Figure 1. Marking of the sample location (green dot) using a map from the company FATMAP (https://fatmap.com/). GPS coordinates: trunk with no spiral grain—N 48°34′57.9″ E 18°59′43.6″; with spiral grain—N 48°34′58.5″ E 18°59′41.0″.

It was necessary to select two types of trees for the research. The first trees were without spiral grain, and the second type of trees with spiral grain (Figure 2). The diameters of the logs without spiral grain averaged about 38 cm, and the logs with spiral grain averaged about 35 cm. It is also possible to see in Figure 2 the amount of lumber that was used for research. For logs without spiral grain, this was 17 pieces of lumber; for logs with spiral grain, it was 14. Five selected samples were measured of the warp crook and warp bow and changes in the spiral grain during three months of air drying (Figure 2).

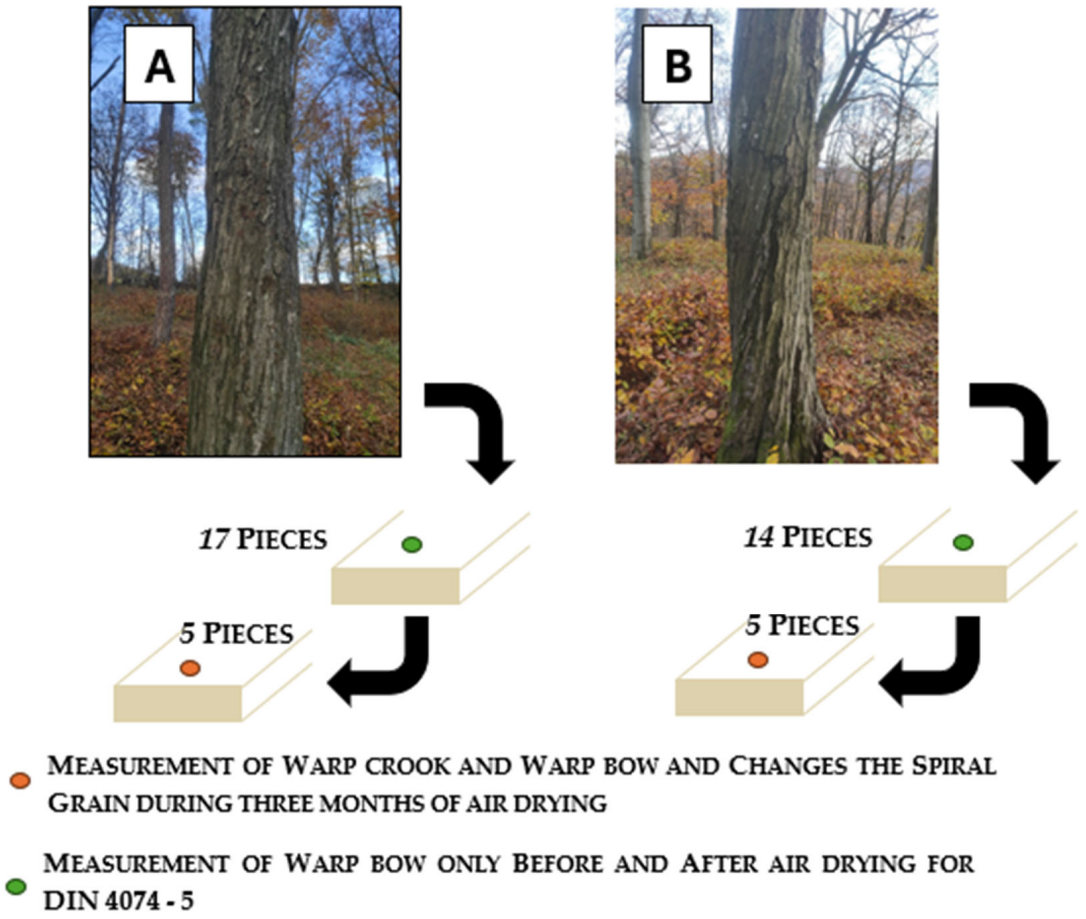


Figure 2. Showed trees without spiral grain (**A**) and with a spiral grain (**B**).

2.1. Preparation of Hornbeam Lumber

A band saw (Mebor 1200, MEBOR d.o.o., Železniki, Slovenia) was used to process the logs. The through-and-through sawing pattern used in the research can be seen in Figure 3. The selection of lumber in a log with or without spiral grain was influenced by visual sorting. Before sawing, the spiral grain was measured on the logs with the spiral grain following the standard [22].

The radial and tangential lumber was obtained by a through and through sawing pattern. Subsequently, it was marked and prepared for edging. While processing logs on the band saw, lumber was marked with numbers so that we knew in which order the logs were processed. Subsequently, to this sample marking, we added the order marking from the main lumber after edging, plus whether the lumber is from the trunk with no spiral grain or with spiral grain. The last data of the marking were the type of lumber, and whether it is tangential or radial, e.g., 6-3/N/R means sixth row (vertically), third in a row (horizontally), N lumber with no spiral grain, R radial lumber. Using an edger saw, the sideboards were removed.

The lumber was thoroughly sorted into radial and tangential. Pieces of lumber with thickness (t) = 0.025 m, width (w) = 0.095 m, and length (l) = 2 m were selected from each log. The selected pieces were placed in the stack. One type of stack is for lumber with no spiral grain, and the other is for lumber with spiral grain. Both stacks (Figure 4) were built on four concrete bases with a height of 0.435 m and 1.80 m apart on a reinforced surface. The lumber in the drying was stacked in the order: tangential–radial–tangential–radial–tangential.

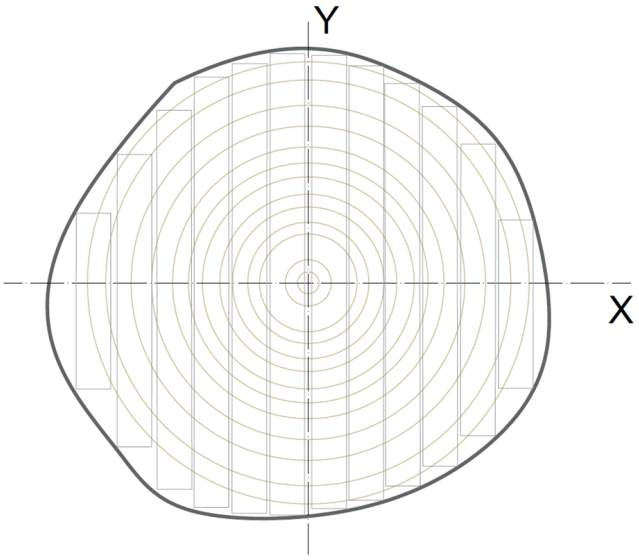


Figure 3. The through and through sawing pattern used in the production of the hornbeam lumber.

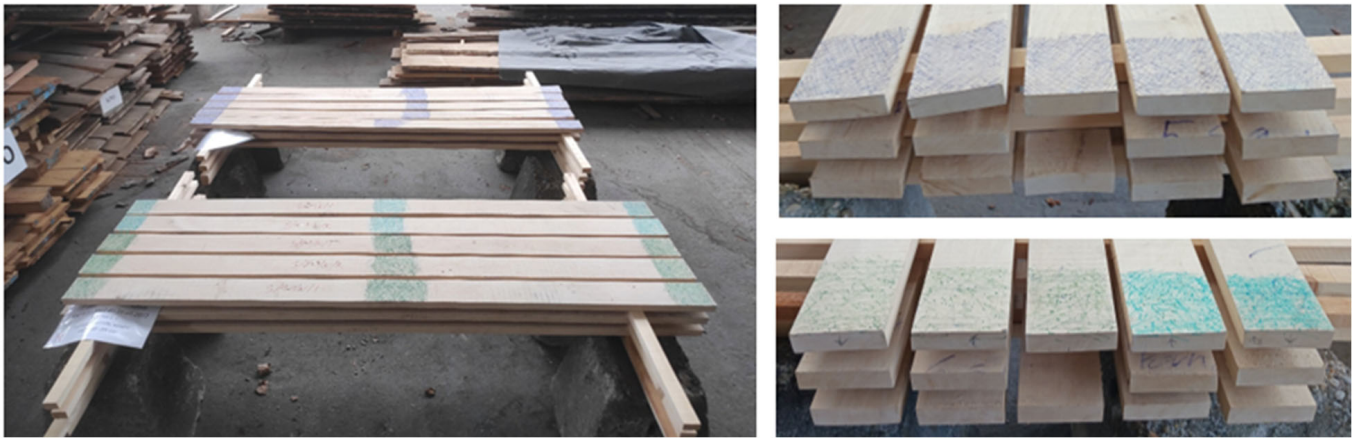


Figure 4. Drying stack for lumber with (pattern of blue) and without (pattern of green) spiral grain.

2.2. Conditions of Air Drying

The air drying was conducted from 10 November 2022 to 14 February 2023. The air-drying conditions were recorded using the device Data Logger Comet S3631 (COMET System, Rožnově pod Radhoštěm, Czech Republic). Hourly intervals were set for the research due to the high accuracy needed in the measured data. The air temperature was recorded in °C and the relative humidity in %.

Moisture loss was detected using a sample coated on both sides with a silicone layer and put in the middle of a stack. The silicone layer was painted to prevent rapid drying of the cross-section of the sample. The reason for applying silicone was the smaller sample compared to the other samples.

2.3. Types of Measurement on the Lumber

The fiber angle of deviation from the log longitudinal axis with spiral grain was measured on the lumber. The angles were measured before and after air drying. The measurements were according to the standard (Figure 5) [22].

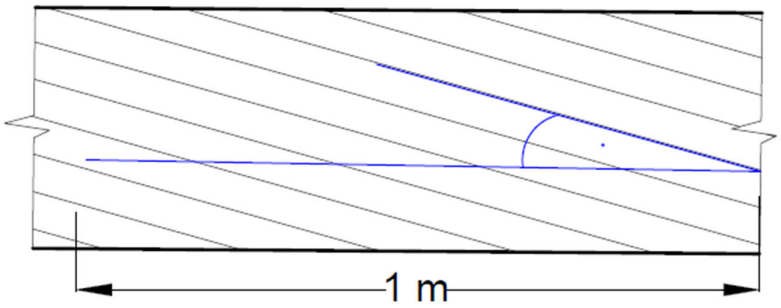


Figure 5. Measurement of the angle of deviation of the fibers from the longitudinal axis.

2.4. Measured Change of Shape by STN EN 1309-3 (49 1013)

As a part of the research focused on the shape stability of lumber, two types of warps were measured: warp bow and warp crook (Figure 6). The measurement was carried out using a digital caliper in the laboratories of the Technical University in Zvolen according to the standard [22].

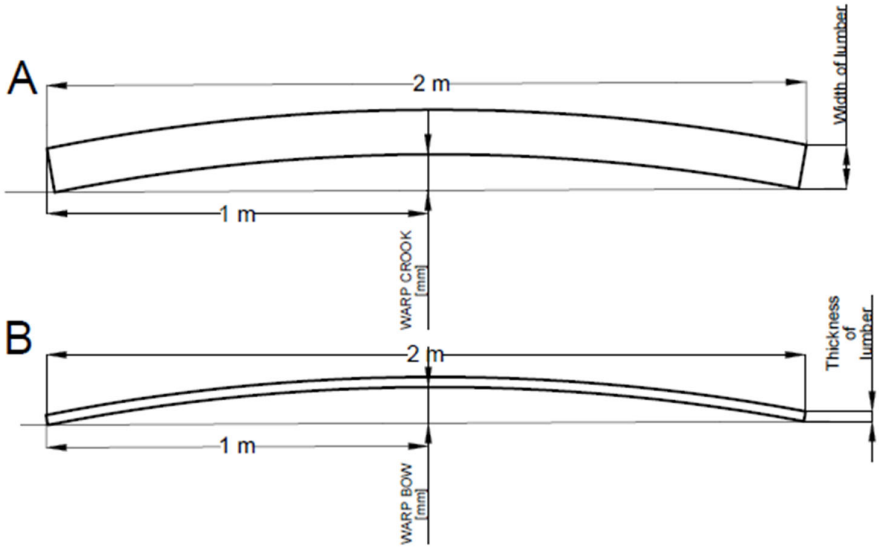


Figure 6. Measured change of shape by [22]: Warp crook (**A**), Warp bow (**B**).

2.5. Classification of Lumber According to Standards

The studies of two types of standards, [23] visually graded hardwood and [24] Standard Practice for Establishing Structural Grades and Related Allowable Properties for Visually Graded Lumber, were used and compared with our measured data.

2.6. Evaluation of Shape Stability by Statistical Methods

All values of warps were also processed at the level of inductive statistics. The analysis of variance ANOVA method was chosen for the above statistical evaluations, which was depicted using a Box 2D graph using a significance level ($p < 0.05$).

3. Results and Discussion

Air drying conditions were recorded, and temperatures ranged from 9 °C in November to −15 °C in February. Relative humidity ranged from 90% in November 2022 to 60% in February (Figure 7).

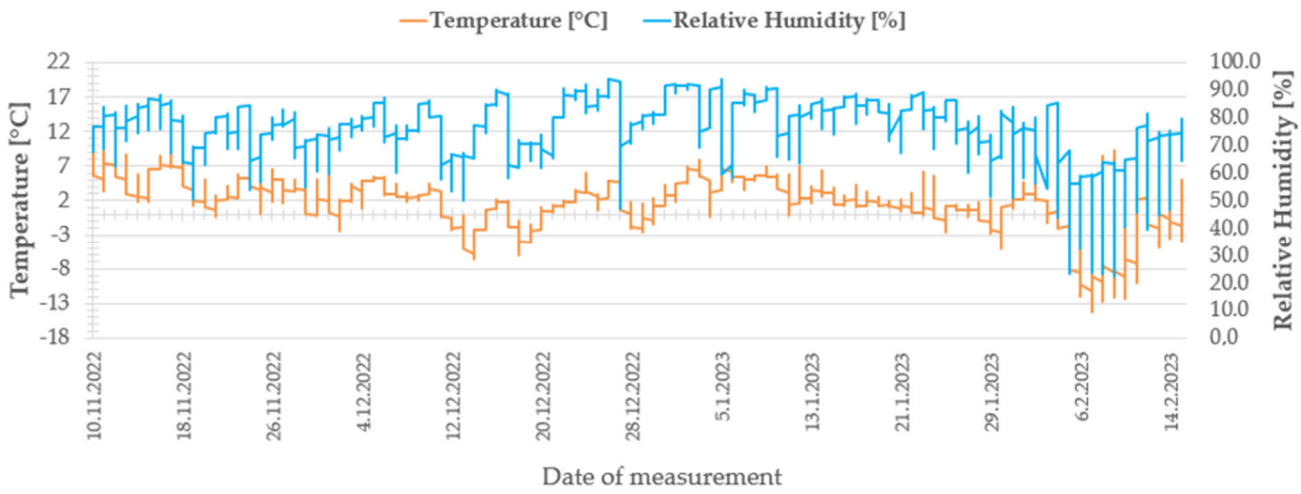


Figure 7. The conditions for air drying during the 3 months of research.

3.1. Changes of Spiral Grain

Wood is an orthotropic material with significant differences in volumetric shrinkage between the longitudinal, radial, and tangential directions during drying.

After the air drying, we first evaluated changes of spiral grain on the surface of the lumber with and without spiral grain (Figure 8). Changes on the surface were detected in the case of lumber with spiral grain, and most on lumber 4-1/To/R, where the spiral grain changed from 5° to 13°. An increase in the deviation of fibers from the longitudinal axis of the sample also occurred in the case of lumber with no spiral grain marked 2-1/N/T, from 0° to 3°. This change could mainly be due to a significant shift in shape, which we detected for lumber with spiral grain in combination with loss of moisture content during air drying. This statement confirmed studies [17,18,20]. Ormarsson [17], based on numerical simulations to determine deformations that develop in lumber during changes in moisture, determined that the most common reasons for formation shape change are spiral grain, reaction wood, location of lumber in the log, etc. Similar results were observed in the research of Ormarsson et al. [18], which discovered that the spiral grain angle and the lumber location within the log were the main contributors to the twist deformation.

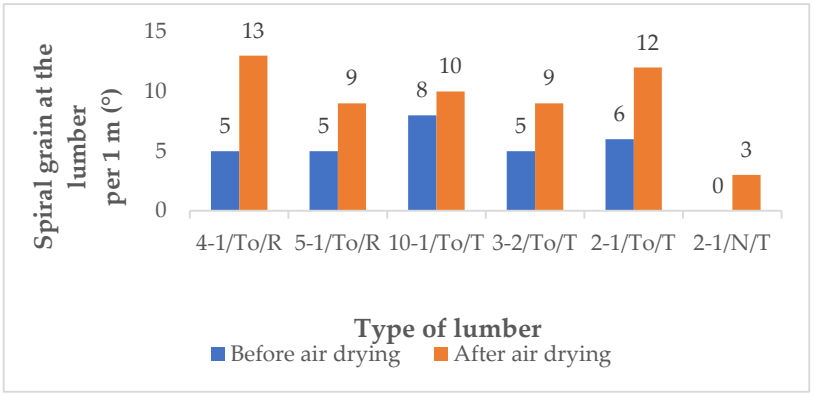


Figure 8. Spiral grain occurring in lumber.

3.2. The Effect of Spiral Grain on Strength Properties

Following the ASTM standard [24] indicating a probable decrease in the strength properties of lumber based on spiral grain, the estimated percentage reductions in bending strength were assigned to the measured data (Table 1). Table 1 shows that strength reduction in lumber with spiral grain should occur in all lumber, which was determined by changes in

spiral grain after air drying, at about 60%. The estimated percentage reductions in bending strength is directly connected with an increase in the grain angle, as confirmed in several research studies [8,10,12]. Authors [2,3] investigated the magnitude of the spiral grain, which has a very marked effect on decreased values for mechanical properties. Results in [2] showed that species such as Beech or Hickory decreased Modulus of Rupture (MOR) by about 44% for Hickory and 55% for Beech, and Modulus of Elasticity (MOE) for Hickory by 47% and for beech by 52%. Similar bending strength decreased in [3] by about 24%, compared to boards of equivalent timber quality. In the case of lumber without spiral grain, the reduction in strength could probably occur only in lumber 2-1/N/T, where there was a change in angle of the grain from 0° to 3° due to shape changes after drying.

Table 1. Estimated reduction in strength according to ASTM D245 [22].

Spiral Grain in Degrees (°)		Strength Reduction in Bending (Experimental)	Strength Reduction in Bending (Numerical Simulation)
		(%)	
4-1/To/R	13	60	50
2-1/To/T	12	60	50
10-1/To/T	10	60	50
5-1/To/R	9	60	50
3-2/To/T	9	60	50
2-1/N/T	3	0	10

3.3. Warp Bow

Figure 9 shows a warped bow during the air drying of lumber containing spiral grain and lumber without spiral grain for three months. In Figure 9A, more considerable shape changes in the observed warps were achieved in the case of lumber containing spiral grain, where the maximum values reached more than 25 mm, compared to lumber without spiral grain, where the maximum values reached only 7 mm (Figure 9B). The most significant warp in a warped bow occurred in the case of lumber 2-1/To/T. This lumber was placed closer to the girth of the log. According to the statistical data processed using the program STATISTICA 13.3, no significant difference was confirmed. This means that the initial position of the lumber in the log did not affect this type of shape change (warp bow). In general, however, several authors claim [18–20,25] that shape changes for warp bow and warp cup depend on the original position in the log.

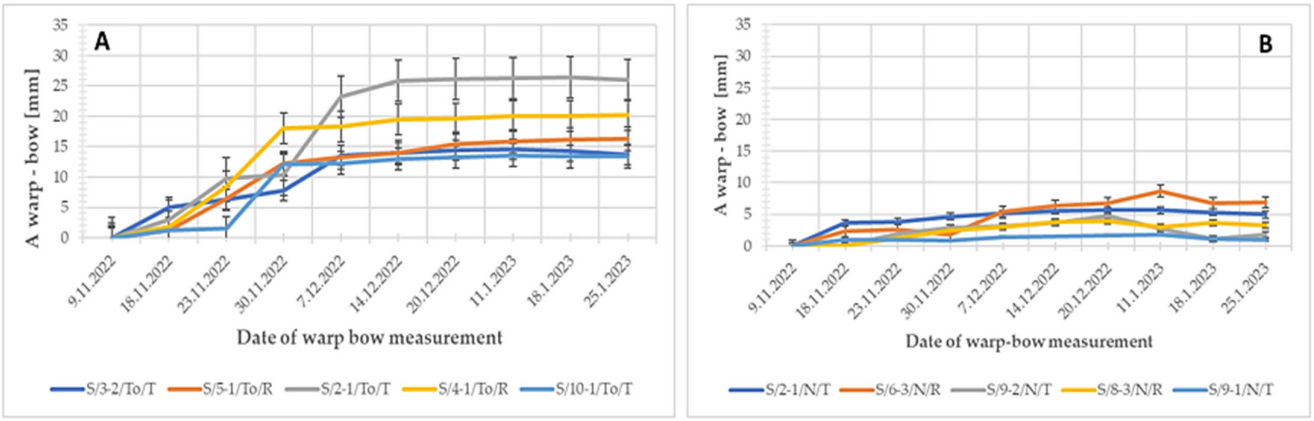


Figure 9. Warp bow (**A**) with spiral grain; (**B**) without spiral grain.

3.4. Warp Crook

Figure 10 shows a warp crook after three months of air drying the lumber containing spiral grain (A), and vice versa without spiral grain (B). It was confirmed that the warp crook was more extensive in lumber containing spiral grain (18 mm) than without spiral

grain (9 mm). The highest values were measured for lumber outside the center (pith) of the log with a spiral grain (2-1/To/T, 4-1/To/T) and even without a spiral grain (2-1/N/T, 9-1/N/T). Results showed that, similar to those for the first shape change (warp bow), it was confirmed to affect the original position in the log on the size measured for shape changes. The results of [17,19,20] showed clearly that shape changes in the lumber are strongly influenced by the original location of the separate pieces within the log and how they are oriented in the products. Their results also showed that material parameters, such as the shrinkage coefficients and the spiral grain angle, considerably influence the warping [20].

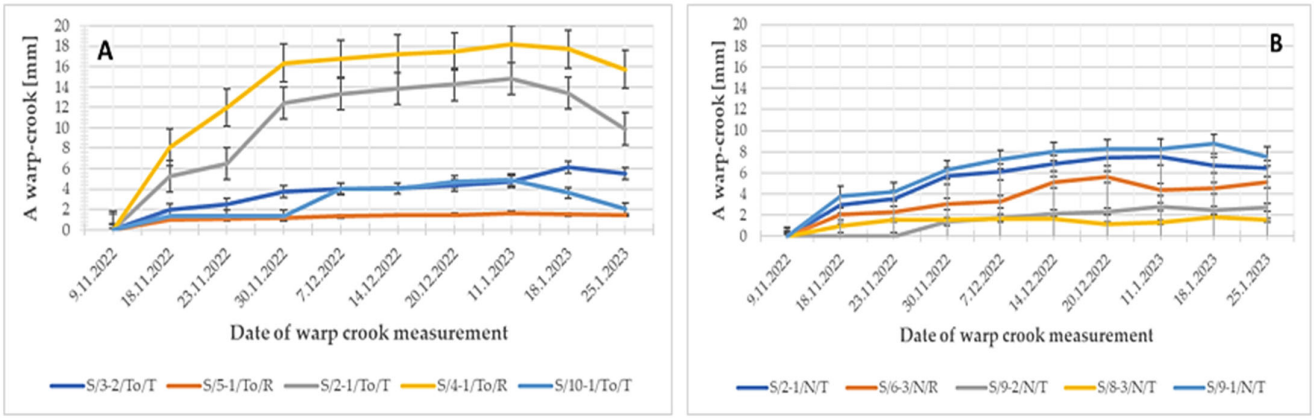


Figure 10. Warp crook (**A**) with spiral grain; (**B**) without spiral grain.

3.5. Visual Evaluation of Shape Changes

After three months of air drying, shape changes in lumber were visually assessed. All lumber from the cage without spiral grain and with spiral grain were disassembled and visually evaluated. Remarkable differences were observed already on the first inspection for comparison (Figure 11 with Figure 12). Remarkable shape changes in the lumber (Figure 11) were caused by a strong spiral grain for lumber (5–8° per 1 m of the length) as well as strong spiral grain for log (0.156 m per 1 m of the length).



Figure 11. Lumber with spiral grain after the three-month research.



Figure 12. Lumber without spiral grain after the three-month research.

Shape changes occur during desorption or with water sorption by wood, around FSB = 30%. The size of the shape changes is not constant; they are different in the cross-section of the lumber. The shape size changes depending on the wood density and the fiber orientation, as also mentioned by [26].

3.6. Classification of Lumber Strength

Lumber was classified into strength classes based on warp bow values following [23]. Lumber was divided into three strength classes (LS $_7$, LS $_{10}$, LS $_{13}$), or it was classified as reclaimed wood because it did not meet even the lowest requirements for classifying lumber in the strength classes LS $_7$, LS $_{10}$, and LS $_{13}$. In the case of lumber with spiral grain, only one sample was included in strength class LS $_7$ (Table 2). On the contrary, for lumber with no spiral grain, 12 pieces were classified (Table 3).

Table 2. Classification of lumber with spiral grain according to the standard (DIN 4074-5) [23].

Classification of Lumber with Spiral Grain According to the Standard (DIN 4074-5)					
Sample	**Bow (mm)-O**	**LS $_7$**	**LS $_{10}$**	**LS $_{13}$**	**Reclaimed Wood**
3-2/To/T	21.49				O
5-1/To/R	18.93				O
2-1/To/T	23.23				O
4-1/To/R	21.94				O
10-1/To/T	17.35				O
7-1/To/R	36.92				O
6-1/To/R	9.68	O			
6-2/To/T	32.59				O
8-2/To/T	26.63				O
3-1/To/T	13.65				O
9-1/To/T	16.26				O
7-2/To/T	26.2				O
8-1/To/R	20.16				O
5-1/To/R	13.34				O

Table 3. Classification of lumber without spiral grain according to the standard (DIN 4074-5) [23].

Classification of Lumber with No Spiral Grain According to the Standard (DIN 4074-5)					
Sample	**Bow (mm)-O**	**LS $_7$**	**LS $_{10}$**	**LS $_{13}$**	**Reclaimed Wood**
1-1/N/R	12.74				O
8-2/N/T	13.14				O
8-1/N/R	10.55	O			
10-2/N/T	10.51	O			
7-1/N/R	11,92	O			
3-3/N/R-T	6.71		O		
2-2/N/T	7.89		O		
11-1/N/T	16.63				O
3-2/N/R	8.68	O			
10-1/N/T	12.98				O
5-2/N/T	17.11				O
6-1/N/R	6.86		O		
2-1/N/T	4.97			O	
6-3/N/R	6.89		O		
9-2/N/T	1.81			O	
8-3/N/T	3.32			O	
9-1/N/T	1			O	

3.7. Statistical Evaluation—Warp Bow

Statistical evaluation based on the Box 2D plot at the significance level ($p < 0.05$) confirmed a significant difference between lumber with and with no spiral grain in warp bow. The resulting p-value for the given warp reached $p = 0.00001$ (Figure 13).

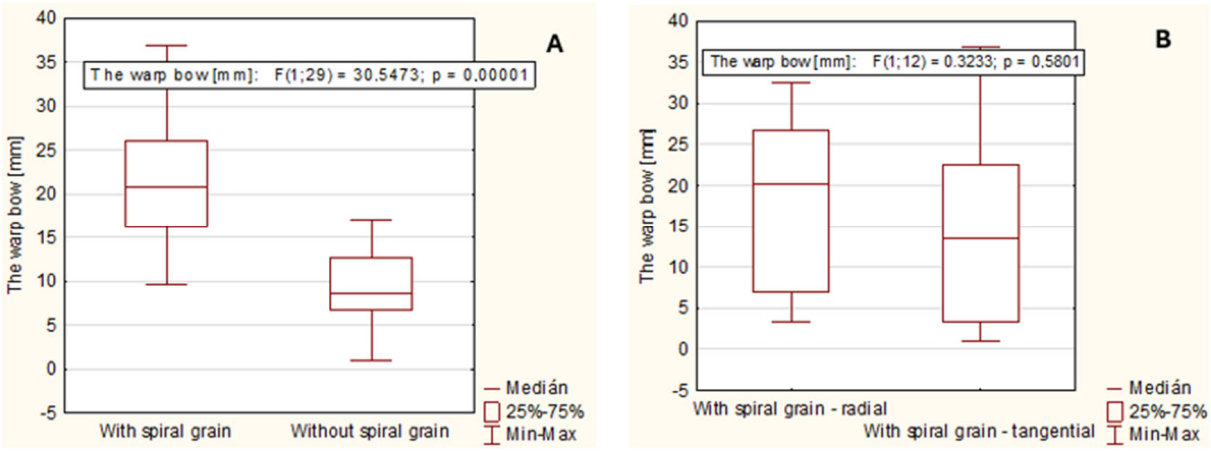


Figure 13. Statistical evaluation. Warp bow (**A**) difference between the log with and without spiral grain; (**B**) difference between tangential and radial lumber.

When comparing tangential and radial lumber, no significant difference was confirmed, which is also indicated by the resulting value of $p < 0.5801$, i.e., the warp does not depend on the initial position of the log, Figure 13B.

3.8. Statistical Evaluation—Warp Crook

In the case of this type of warp, i.e., a warp crook, there is a significant difference between the two types of logs with and with no spiral grain. The final p-value for warp crook reached $p = 0.0436$, Figure 14A.

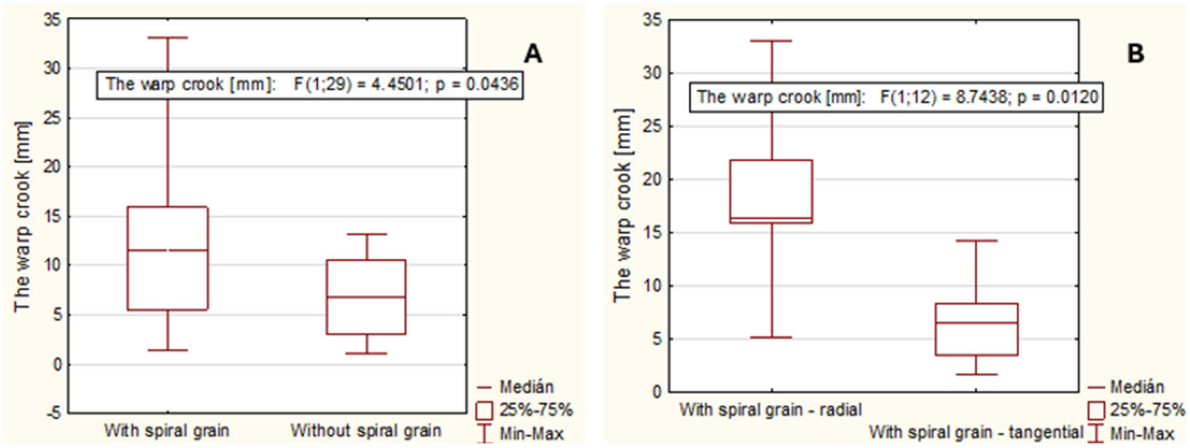


Figure 14. Statistical evaluation. Warp crook (**A**) difference between the log with and without spiral grain; (**B**) difference between tangential and radial lumber.

A significant difference was confirmed after comparing tangential and radial lumber, also indicated by the resulting value from the STATISTICA program, which was 0.012. Therefore, the warp depends on the initial position of the log during the first stage of wood processing (Figure 14B).

4. Conclusions

- Our research confirmed that the spiral grains remarkably affect shape stability. A warped bow with spiral grain values increased by almost 50% compared with lumber without spiral grain. This statement was confirmed even with statistical results where the set limit value of $p < 0.05$ was not exceeded, either with warp crook ($p = 0.0436$) or with warp bow ($p = 0.00001$).

- Regarding warp crook, statistical significance was also confirmed for different types of lumber (radial or tangential), where the significance value reached $p = 0.0120$. This result can be explained mainly by the original position of tangential lumber, which was closer to the girth of the log, than radial lumber, which was closer to the pith, which could lead to different shape stability.
- According to the measured values, the warps during the warp crook depend on the sizes of the spiral grain and the original position of the lumber, which means whether the lumber is closer to the girth of the log or closer to the pith.
- According to DIN standard (4074-5) and sizes of shape change for warp bow, only one piece of lumber would be obtained in the case of lumber with spiral grain and up to twelve pieces of lumber in the case of sawn lumber without spiral grain. This result confirms that the spiral grain remarkably influences the resulting quality of the lumber.

This research could broaden the possibilities of using hornbeam lumber (*Carpinus betulus* L.) as a construction material.

Author Contributions: Conceptualization, I.K. and P.V.; methodology, H.M.U. and I.K.; software, P.V. and I.K.; validation P.V. and I.K.; formal analysis, P.V.; investigation P.V.; resources, T.V.; data curation, I.K.; writing—original draft preparation, P.V.; writing—review and editing, T.V.; visualization, H.M.U.; supervision, I.K.; project administration, P.V. and T.V.; funding acquisition, I.V and P.V. All authors have read and agreed to the published version of the manuscript.

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